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COMPUTER SIMULATION OF TEMPERATURES ON THE CENTAUR STANDARD SHROUD DURING HEATED JETTISON TESTS

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ABSTRACT

In anticipation of a series of heated jettison tests to be conducted on the Centaur Standard Shroud at the NASA Plum Brook Station's Space Power Facility, a heating fixture was built to provide a simulation of the heating and environment encountered by the Centaur Standard Shroud during its ascent through the earth's atmosphere. A computer program was developed to provide a means of determining the overall temperature profile of a free-skin model of the Centaur Standard Shroud during the heating portion of the heated jettison tests. The program is unique in that it treats the energy contribution of each lamp on the heater to various points on the Centaur Standard Shroud surface. The analytic model was verified by adapting the computer program to the configuration of the hardware used in a series of Intermediate Scale Tests performed on a 2.4 meters by 2.4 meters section of the Centaur Standard Shroud corrugated structure. A comparison of some predicted versus experimental results from these tests is presented.

INTRODUCTION

A series of heated jettison tests on the Centaur Standard Shroud (CSS) is being planned for the fall of 1973 at the NASA Plum Brook Station's Space Power Facility (SPF). The CSS is to be heated during these tests using an infrared lamp heating fixture and in an air pressure environment of about 2700 newton/m^2 or 20 torr (equivalent to approximately 20,700 meters or 68,000 ft altitude). At the conclusion of the heating cycle, the heater halves are to be retracted and the CSS Super-Zip explosive seams and hinge spring system are to jettison the CSS halves into catchnets. During the jettison, high speed motion picture cameras will record the movements of the shroud.

One of the primary purposes for performing these tests at SPF is to provide data to be used in the verification of thermal and mechanical analytical models being developed at Lockheed Missiles and Space Company (LMSC), the designer and builder of

the CSS. The steps in the verification and use of these models are as follows: (1) Using the thermal data from the CSS tests, one analytical model will be developed and used to define the temperature distribution throughout the CSS structure. (2) The temperature distribution defined by the thermal model will be used in another model to define thermal stresses during the heating phase of the tests and subsequent motions of the CSS during jettison. Strain gauges, accelerometers, cameras, and other instrumentation will provide data for use in verifying this model. Some anticipated motion modes include a hot-dogging or banana effect (because of the unequally distributed thermal stresses) during heating of the CSS, and flapping and twisting motions during jettison. (3) Finally, these models will be used to reliably predict CSS motions during jettison with heating profiles encountered in other possible flight trajectories and to determine whether the CSS structure will impact any flight experimental package envelopes (such as the Mars Viking mission payload).

In support of the above program, test equipment designers determined that a means was required to predict what the actual heating profile would be on the CSS during these tests. A free-skin model of the CSS/heater system was incorporated into a computer program to carry out this function. The reasons for this choice can be summarized as follows: (1) The size of the CSS/heater system and the fact that the thermal response over the CSS surface varies continuously throughout the 4-minute test cycle makes the dimensions of the problem much too large to handle without the aid of a computer. (2) In designing the test configuration, it was necessary to provide a basically radiation simulation of the convection heating encountered during a flight trajectory. Because it is impossible to exactly simulate convection heating with a radiation heat source, it was desirable to provide the means to determine how much the actual temperature profile during the heated jettison tests would deviate from the anticipated trajectory heating profile. (3) End effects in the CSS/heater system were not taken into account in the heater design, except for providing reflectors to prevent radiation losses. It was therefore also desirable to know how much the temperatures at these points would vary from the design condition.

SCOPE OF THE PROBLEM

The scope of the problem can be seen from a brief consideration of test hardware, configuration, and requirements.

Centaur Standard Shroud

The overall dimensions (in inches) of the CSS is shown in figure 1. The thermal analysis is complicated by the existence of multiple surfaces (eight), different materials (aluminum and

and magnesium alloys), also indicated in figure 1. The skin is riveted to a frame consisting primarily of Z-shaped aluminum circumferential rings spaced at 38.1-centimeter intervals along the CSS axis. Additional structural elements include field joint rings at the various CSS surface intersections and the special Super-Zip explosive seams which split the CSS into two halves at jettison.

Centaur Standard Shroud Heater

The CSS heater, illustrated in figures 2 and 3, consists of an aluminum I-beam frame covered with a 0.305 centimeter polished and anodized aluminum reflector material. General Electric 1000-watt infrared quartz lamps (5910 on the full sized heater, 388 on the Intermediate Scale Tests' heater) are mounted on anodized bus bars attached to the reflector surfaces. The bus bars are mounted on the lamp side of the reflector surfaces to minimize potential arcing problems at the electrical penetrations of the reflector surfaces. The lamps are divided into 18 separate heating zones, 11 on the cylindrical section and seven on the conic sections of the heater. Each zone consists of two equally-sized and symmetrically-located halves. These heating zones run parallel to the CSS axis and are distributed circumferentially as shown in figures 4 and 5. Separate controllers provide power to the lamps in each heating zone.

Power Controllers

Power to the lamps in each heating zone originates from a three-phase, 416-volt supply and is varied using a specially designed Zee Power Control System. The signal from a thermocouple mounted on the Z-ring side of the shroud skin midway between Z-rings is used as one input to the power controller. The output from a rotating drum programmer device, on which the desired temperature response is scribed (a sample control temperature history is shown in fig. 6), is the other input to the power controller. The difference from these input signals is used to vary power by varying the portion of the a.c. voltage cycle, through the use of silicon-controlled-rectifiers (SCR's), during which current is provided to the lamps on the heater. The power history of each controller is recorded on the XDS 930 data acquisition computer and is necessary input for the temperature prediction program.

Control and Abort System

During the heating portion of the tests, a set of two thermocouples mounted adjacent to control thermocouples and another set in similar position in the second half of the control zone are monitored. The temperatures read from each of these pairs are compared with curve fits of the respective temperature control curves. These comparisons are performed in

the main component of the Test Control and Abort System, a PDP8E minicomputer. If the control temperature, as represented by a pair of thermocouples previously noted, deviates from the desired control temperature by predetermined limits, the test is automatically terminated. Both thermocouples in a pair must be out of limits in a half-zone before a test abort will occur.

Data Acquisition System

The same thermocouple pairs mounted in the Control and Abort System are also monitored, and compared with control temperature history curve fits, by the XDS930 computer used at SPF for data acquisition. Alarms are provided in this system again when both thermocouples in the monitored pairs deviate from their predetermined limits, allowing this system to be used for backup control and abort purposes.

Approximately 300 total temperatures, as well as signals from other instrumentation sources, are recorded by the XDS930 computer. The data from this instrumentation is available in engineering units soon after the completion of a test for test evaluation purposes.

Test Configuration and Requirements

The overall test configuration is shown in figures 2 and 3. The CSS/heater system is located in the 30.5-meters diameter by by 36.6-meters high space simulation chamber at the Space Power Facility. The spacing between the heater reflector and the CSS outer surface is approximately 30.5 centimeters and the lamps are placed approximately 7.6 centimeters from the reflector surfaces.

A typical test heating cycle (based on time from liftoff to CSS jettison) is 280 seconds. The predicted trajectory temperature profile varies both circumferentially and axially over the CSS surface and with time. Typical circumferential and axial profiles are shown in figures 7 and 8. The actual heater design provided for a flat temperature distribution over each CSS section axially and over each half-zone circumferentially. The actual temperature distribution will be influenced by end effects between these heating areas. The circumferential location of the maximum temperature, which occurs on the windward side of the CSS during flight, will be skewed from the separation joint plane in the first heated jettison test (nominally by 32°) and aligned with it the second test, as illustrated in figure 9. The zone configuration for these tests is shown in figures 4 and 5.

METHOD OF APPROACH TO PROBLEM

During the original consideration of the problem of analyzing heater operation, a literature search was conducted in an attempt to find analytic tools that had already been developed which could be applied to the test configuration. No references were found concerning programs or documents which could function as the necessary analytic tools. The basic missing item concerned the treatment of heat output from individual lamps in a radiant heating system. This was considered to be a significant requirement because of the energy input discontinuities at surface intersections on the CSS (as illustrated in fig. 8) and was the primary consideration in the decision to develop a new computer program to handle the problem.

In reviewing the literature concerning radiant heater systems, the conceptual requirements for the program were defined. This resulted in a number of assumptions that were made to fit the anticipated test configuration. The thermal model used in the program was designed around these assumptions, which in summation include the following: (1) Because of the difficulty in analyzing the lamp filament and envelope as cylindrically-shaped heat sources, the decision was made to treat the 25.4-centimeters long filament/envelope combination as a string of ten-point sources. (2) The reflection of lamp radiation off the aluminum reflector sheets was treated as totally specular in nature. This permitted treatment of lamp reflections as an additional series of point sources, reduced in intensity by the amount of energy absorbed by the reflectors. (3) The reflector surfaces were treated as diffuse emitters and were treated as diffuse absorbers of radiation from low-temperature sources. (4) CSS surfaces, which are covered with a radiation-absorbing coating, were treated as both diffuse emitters and diffuse absorbers. (5) The CSS corrugated skin was treated as a single layer of material with an effective skin thickness. This approach produced consistent results in early LMSC development work. It also permitted future modifications by adding an appropriate nodal network to improve prediction results, if so desired. (6) The thermal model used is a free-skin model, that is, energy absorption by internal structural elements is not treated. This approach was used because the principal purpose of the program was to verify that the correct energy input distribution was being provided over the CSS. Comparison of predictions with early test data showed that the effect of structural elements on the CSS skin at points farthest removed from these structures was minimal and, therefore, the temperatures at these points were comparable to having a shroud with no internal structure. (7) Circumferential and axial heat conduction through the skin was treated as being negligible because of the comparatively low anticipated temperature differential per unit circumferential

length and because of the thin skin thickness. (8) Convection effects, which exist to a minor degree in the 2700 newtons per square meter test environment, were not included in the program. To do so would require a more extensive nodal system and does not appear to be required based on test results.

DESCRIPTION OF COMPUTER PROGRAM

The basic structure of the computer program consists of two primary parts. The first section of the program is setup to define the basic CSS/heater configuration. The coordinates of the centers of each lamp filament increment, and all of its reflections (including those in the end reflectors), are defined. These coordinates are used to calculate unit heat fluxes, similar in concept to geometric view factors, at various points on the CSS surface. These unit heat fluxes (in units of $1/\text{inch}^2$) are defined by the following equation:

$$F = \frac{(\cos \phi)}{4\pi} \times \frac{R_L \cos(\theta_L - \theta_S) - R_S + (Z_L - Z_S) \tan \phi}{\left[R_L^2 + R_S^2 - 2R_L R_S \cos(\theta_L - \theta_S) + (Z_L - Z_S)^2\right]^{3/2}}$$

where R_L, θ_L, Z_L are lamp increment cylindrical coordinates

R_S, θ_S, Z_S are CSS point cylindrical coordinates

and ϕ is angle of a conic surface with its axis

These unit fluxes are summed for all lamp increments of a similar degree of reflection and multiplied by a factor representing the energy output per lamp filament increment length. This factor is based on the power being applied to all the lamps in a given heating zone. The resultant overall sum provides an incident heat flux from the lamps and reflections to the point being considered on the CSS, in units of Btu/sec-ft^2.

The second section of the program makes use of the incident heat flux at a CSS point determined in the first section. This section of the program defines an energy balance in the system. Radiation losses from the shroud to the reflector are calculated, based on local CSS and reflector temperatures. Incident lamp energy on the reflector surfaces is approximated based on the calculated incident heat flux on the CSS. Finally, net heat inputs to both the CSS and the reflector at a given CSS surface normal are calculated and are used to define the temperatures at these points, taking into account the thermal capacity of the skin per unit area.

In summary, the thermal model used in the program is three-dimensional from a radiation heat transfer viewpoint but only one-dimensional in considering CSS conduction through the skin. This free-skin model permits a fairly accurate representation of the actual thermal profile over the CSS surface. The program can be used to consider a large number of points over the CSS surface, thereby providing a temperature mapping, or can look at a limited number of points, such as thermocouple locations, and compare the predicted with experimental results.

VERIFICATION OF THE ANALYTIC MODELS

The computer program was adapted to the configuration of the hardware used in a series of Intermediate Scale Tests (IST's) performed at SPF. Temperatures were predicted on the corrugated skin panel used in these tests and were compared with the experimental data.

Centaur Standard Shroud Intermediate-Scale Tests Configuration

The configuration of the IST's was designed to as closely approximate the heated portion of the CSS heated jettison tests as was possible with the test hardware being used. The target heated test panel consisted of a 2.4-meters by 2.4-meters corrugated panel structure, in all respects similar to the hardware used on the upper portion of the cylindrical surface of the CSS. The panel was enlarged using sections of single-thickness aluminum, the thickness being equivalent to the effective thickness* of the corrugated skin as used in the thermal model. Enlarging the test panel area was required to make the heater of sufficient size to be able to test a single power controller at its full 360-kilowatt power capability. The same insulation used internally on the CSS covered the Z-ring side of the IST test panel, in order to minimize surface heat losses from that side of the panel.

The heater consisted of a similar cylindrical section as the CSS test panel, all hardware being the same as configured in the full-scale heater. Circumferentially, the heater included eight half zones. Because the heater was powered with only either one or two controllers, the lamp distribution varied circumferentially in order to obtain a circumferential temperature distribution.

Fifty-three test runs were performed on the CSS IST hardware. These tests were run in three air environments: (1) 101,300 newtons per square meter or normal atmospheric pressure;

*The effective skin thickness used in the design was incorrect, resulting in higher than anticipated temperatures on these "dummy" test panel sections.

(2) 2700 newtons per square meter, the anticipated full-scale test environment; and (3) 0.007 newtons per square meter, or hard vacuu. The lamps were powered with either a single controller supplying all eight heating zones or each of two controllers supplying four heating zones. The control temperature profiles consisted of either a typical LMSC flight trajectory temperature history, or a "square wave", which tested the controller at full power until the control temperature reached the plateau temperature.

Comparison of Predicted and Experimental Temperatures

The Intermediate-Scale Tests version of the computer program predicted temperatures at thermocouple locations and compared these predictions directly with experimental data. A sample of the results of this comparison is shown graphically in figure 10. Overall, comparing the experimental data with predicted results showed maximum deviations of the order of ± 17 degrees Celsius. This deviation usually peaked near the end of the 4-minute test cycle, which involved a temperature rise from ambient (21 degrees C) to temperatures of the order of 215 degrees Celsius on the CSS test panel.

Further studies are being made for conditions which might be influencing the temperature predictions. For example, one that has been discovered but which at the time of this writing has not been accounted for in the CSS IST model, concerns lamp power levels. The IST heater lamp configuration was such that the number of lamps could not be divided equally among the three-phase power source. The result was that individual lamp energy output varied somewhat in proportion to this load imbalance.

CONCLUSIONS

In general, it appears that the effectiveness of the thermal model used in the developed computer program has been proven in its adaptation to the CSS IST configuration. Efforts are continuing to improve the accuracy of the thermal model, prior to and during the actual heated jettison tests by: (1) increasing the number of nodes considered at a given area of the CSS, and (2) investigating the significance of heat transfer modes and paths other than those considered in the model.

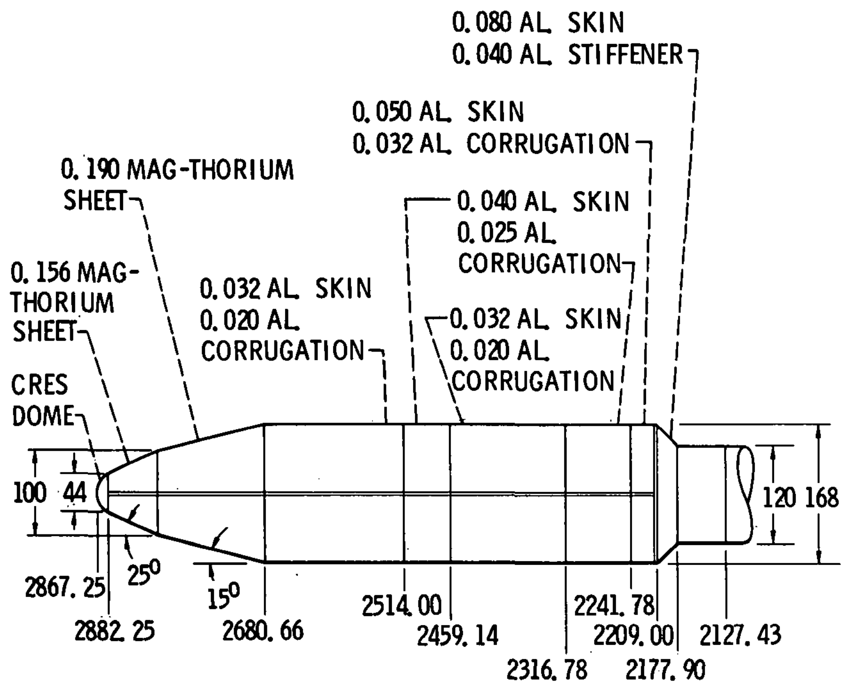


Figure 1. - Structural configuration.

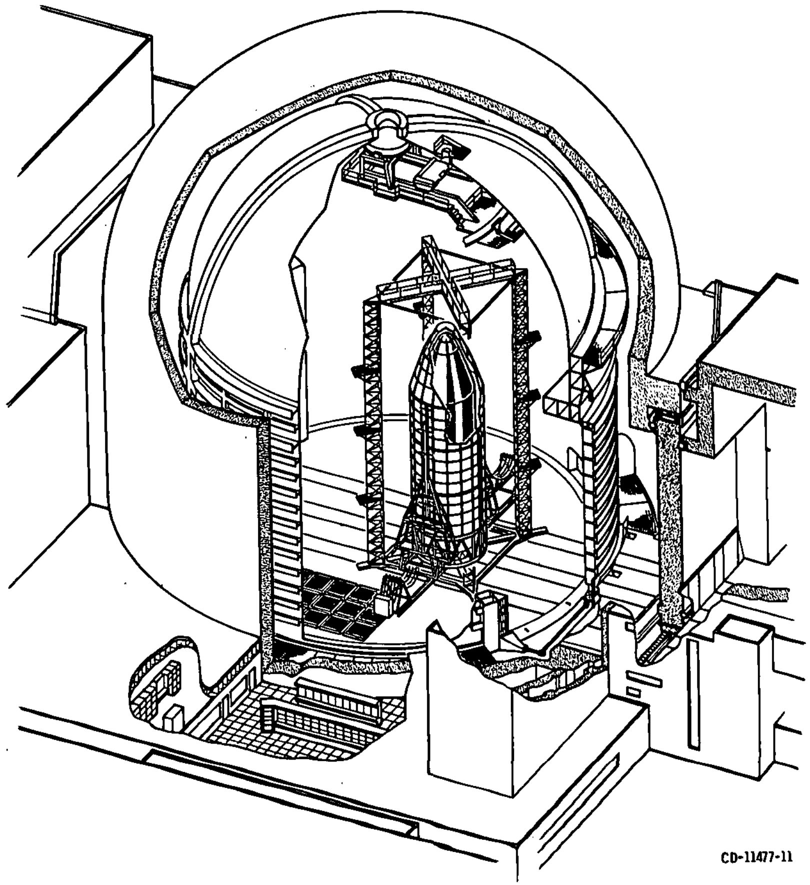


Figure 2. - Centaur standard shroud in space power facility.

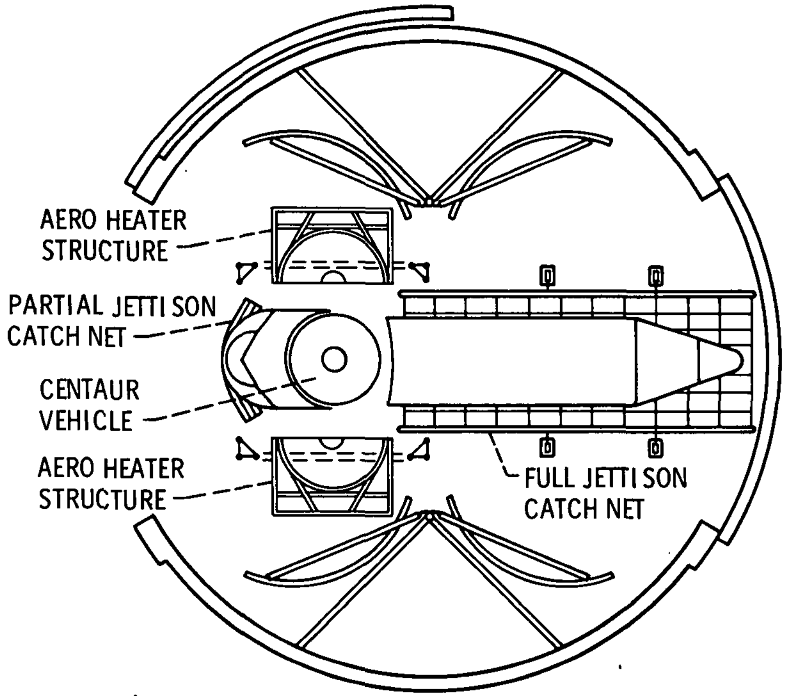
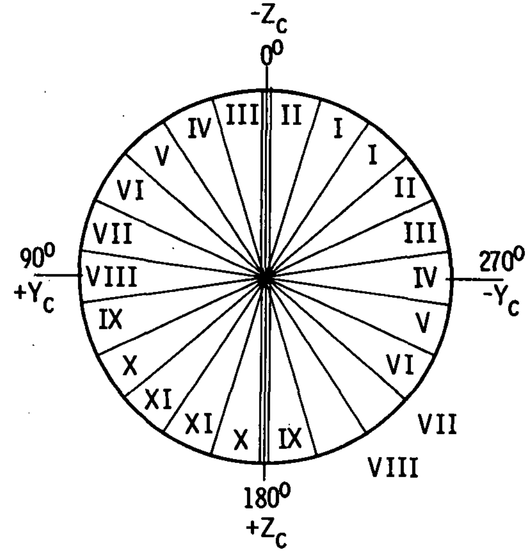
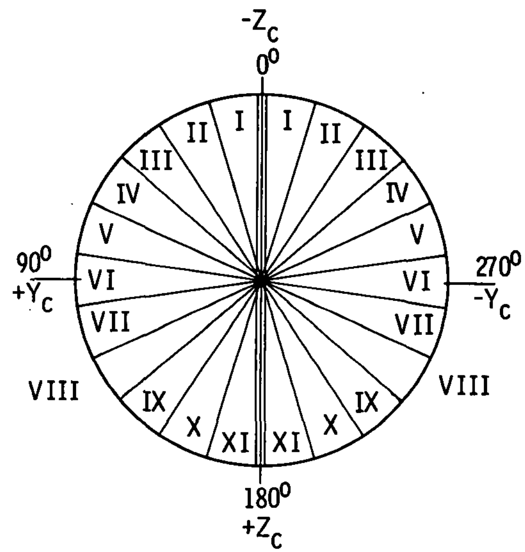


Figure 3. - Space power facility Centaur heated shroud jettison test.

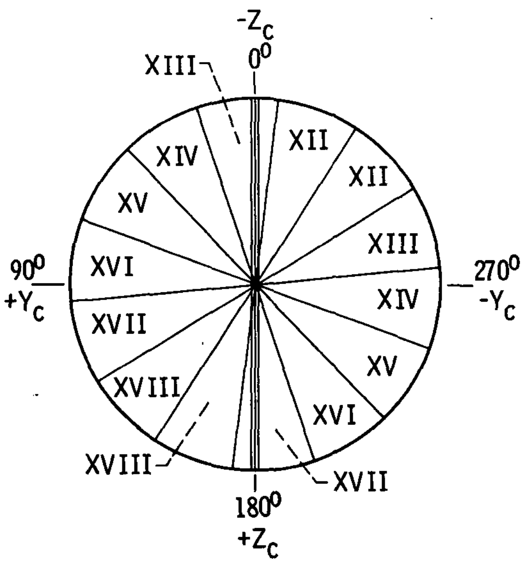


(a) 32^0 SKEW TEST.

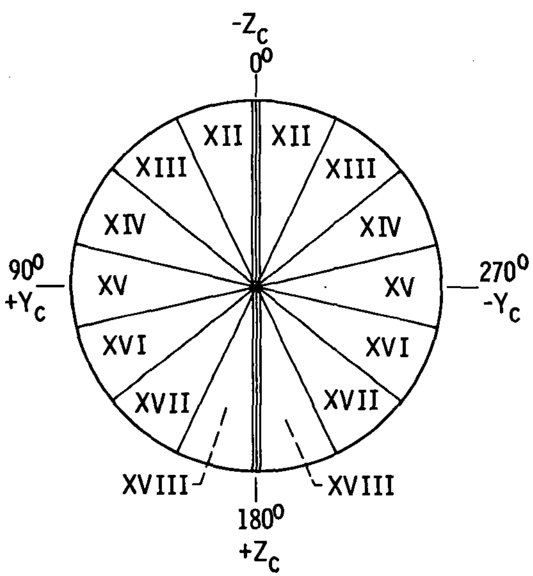


(b) 0^0 SKEW TEST.

Figure 4. - CSS cylinder control zones.



(a) 32° SKEW TEST.



(b) 0° SKEW TEST.

Figure 5. - CSS conic control zones.

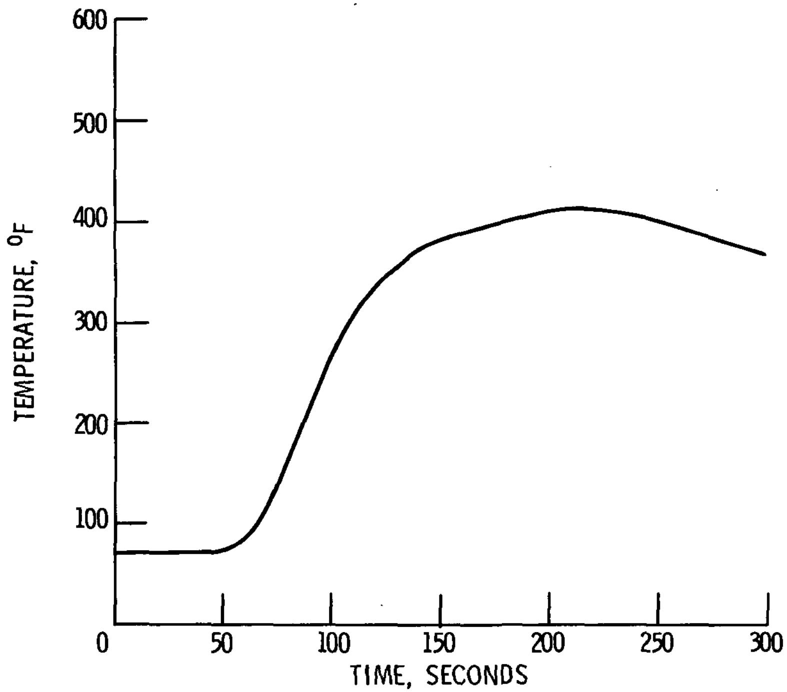


Figure 6. - CSS cylinder control zone 1 at leading edge (RH758B).

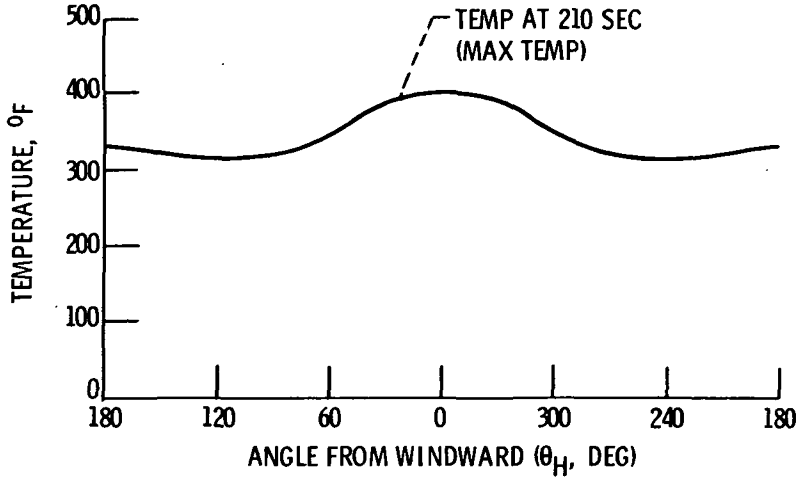


Figure 7. - Free skin circumferential shroud temperature distribution predictions for cylinder leading edge (RH758B).

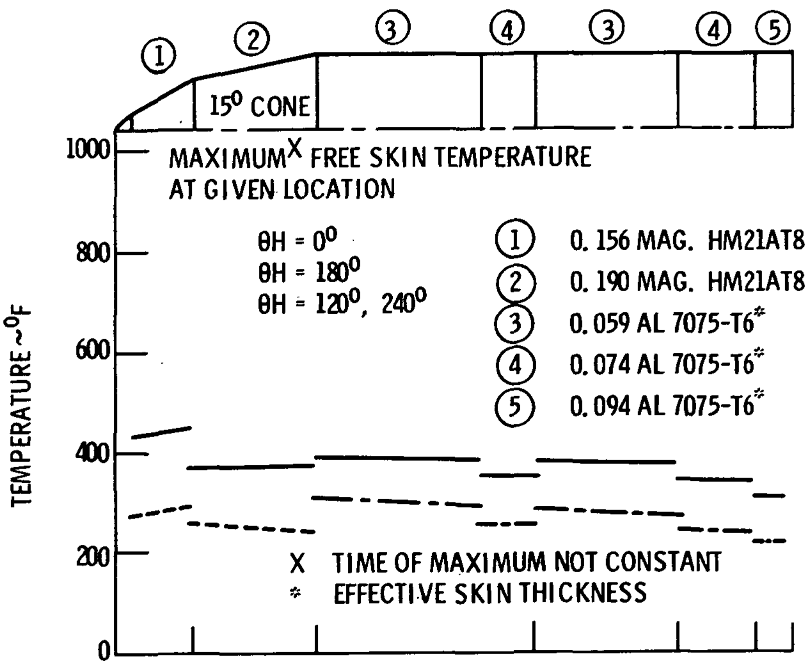


Figure 8. - Free skin axial shroud temperature distribution prediction (RH758B).

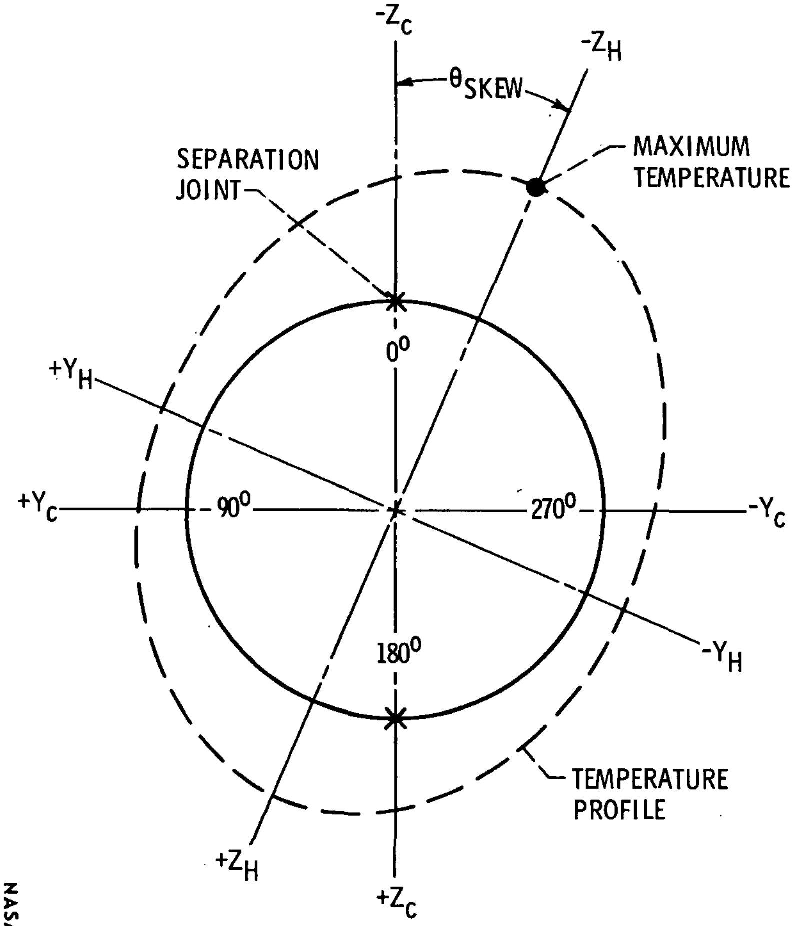


Figure 9. - Skewed temperature distribution on cylinder.

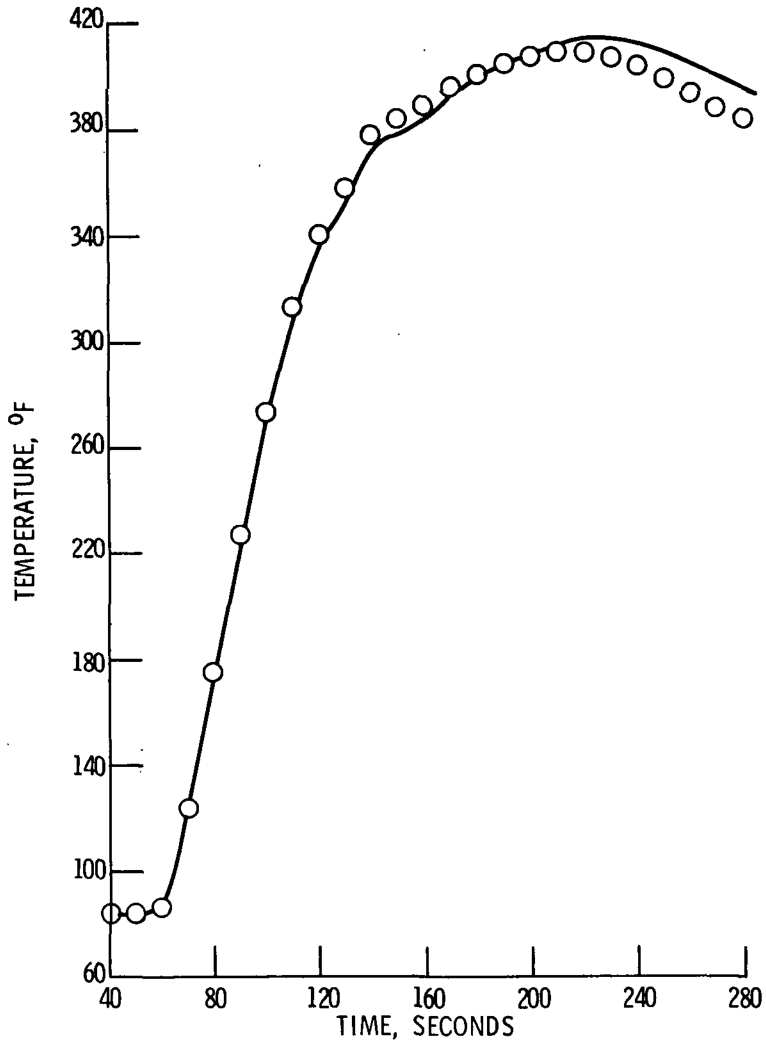


Figure 10. - CSS intermediate scale tests. Run, 41; thermocouple, 11; predicted temperature response and experimental data shown as functions of time.